Laser Produced EUV Light Source Development for HVM

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Outline

- Introduction
  - LPP source roadmap and concept
- Topics
  - Breakthrough of LPP EUV power
  - Easier debris mitigation of CO_2 laser produced Sn plasma
- Characteristics of a CO_2 laser produced Sn plasma source
  - Conversion efficiency
- LPP/EUV future direction to HVM
- Summary

LPP Source Roadmap

	1st Mid term 2004/9	2^{nd} Mid term 2006/3	EUVA Final 2008/3	HVM source-1 2010
EUV Power (IF)	5.7W [1)]	10W [1)]	50W [2)]	110W [2)] /140W [3)]
Stability	---	s<±10%	s <±5%	3s<±0.3%
Laser	YAG:1.5kW	CO_2:2.6kW	CO_2: 7.5kW	CO_2: 10kW
Laser freq.	10kHz	100kHz	100kHz	100kHz
CE (source)	0.9%	0.9%	2.5%	4%
Target	Xe-Jet	SnO_2 choroid liquid jet	Sn-Droplet	Sn-Droplet

Technology for <10W
Nd:YAG Laser, Liquid Xe jet

Technology for 115-200W
CO2 Laser, Sn droplet target
Magnetic field mitigation

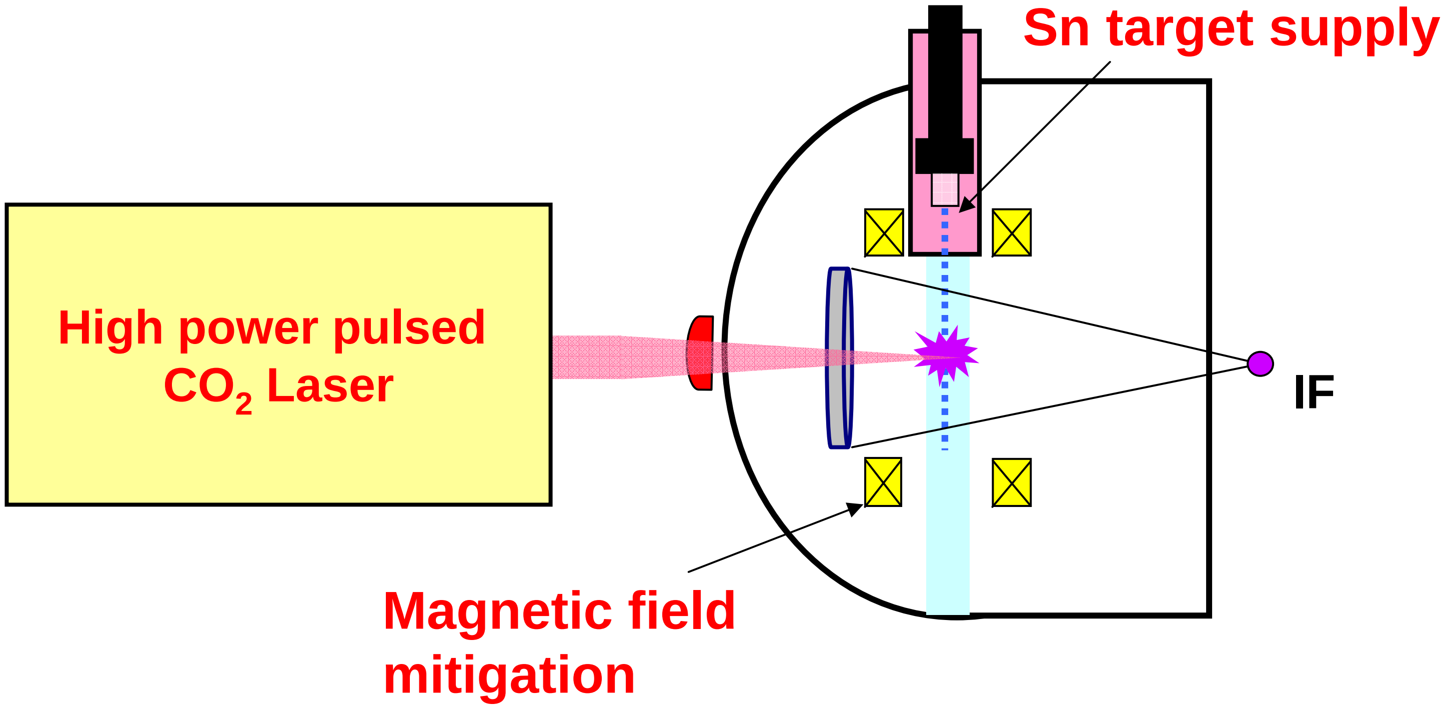
Note）
Primary source to IF EUV transfer efficiency:
1) 43%
2) 28% with SPF
3) 36% without SPF

Light Source Concept

Requirement for EUV source for HVM

- High EUV power >115 W
- EUV Stability
- Collector mirror lifetime
- Low CoG / CoO

CO_2 laser + Sn LPP light source + Magnetic field mitigation



Concept of CO_2 laser produced Sn plasma source

EUVA **original** concept:

CO_2 laser + Sn LPP light source for HVM EUVL

Advantages

- Superior laser performance
  - Power expandability with high beam quality ← Topics 1
  - Lower CoG and CoO
- Higher CE at low laser intensity
  - Maximum CE of 4.5% at low laser intensity ← Fundamental **exp.**
  - Narrow spectrum at 13.5 nm
- Low debris
  - Drop-debris free with Sn plate target ← Topics 2
  - Magnetic mitigation applicable (large space because of LPP)

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Topics Summary

1. Breakthrough of LPP EUV power

   40W @I/F equivalent EUV power was produced from CO_2 laser produced Sn plasma. (source power 110 W, 2π sr, 2%bw)

2. Easier debris mitigation of CO_2 laser produced Sn plasma

   Debris mitigation of CO_2 laser produced Sn plasma experiment shows marvelous promising data.

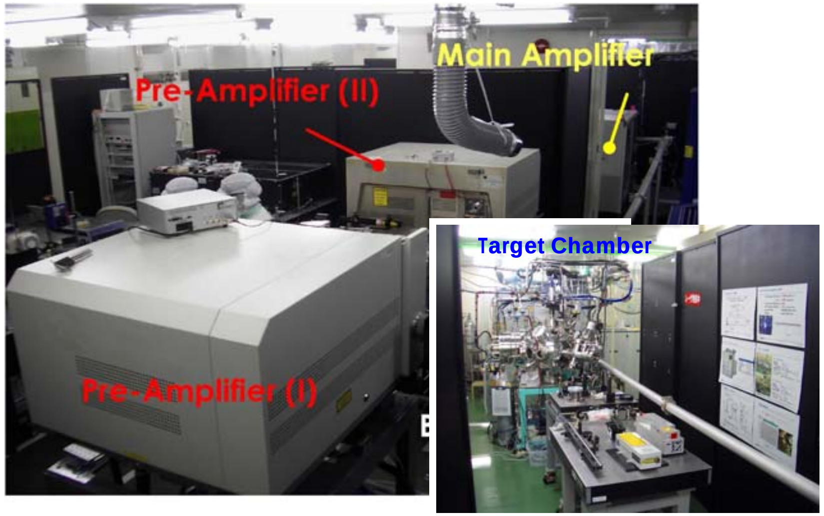
   - Very small Sn deposition on collector mirror
   - Drop debris free Sn plasma

Experimental devices for EUV source development

Component development are driven by two experimental devices.

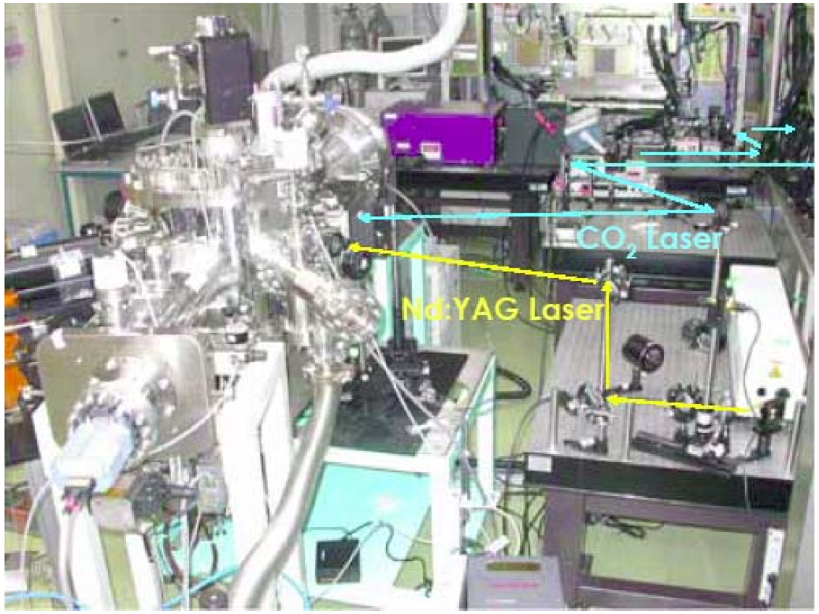
1. High power experiment device

- RF-CO_2 laser based system
- High power laser system development
- Target development
- High power EUV generation



2. Fundamental experiment device

- TEA-CO_2 laser based system
- CE experiment
- Debris analysis
- Mitigation system development



High Power CO_2 Laser MOPA System

High power experiment device

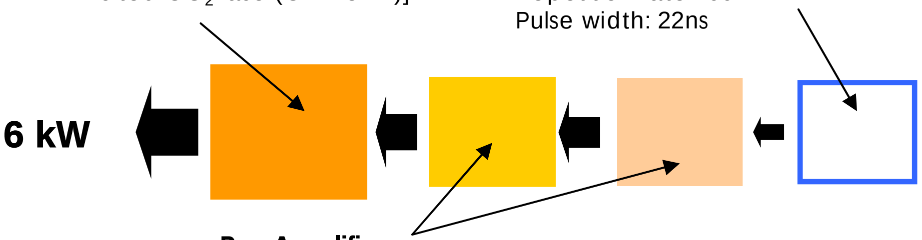
■ Performances

Laser Power:	6 kW
Pulse Width:	22 ns
Repetition Rate:	100 kHz

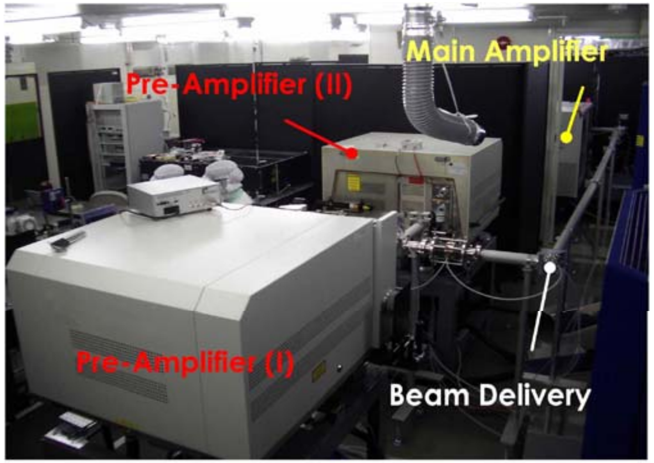
■ Laser System

Main-Amplifier
[Fast Axial Gas Flow
RF-Excited CO_2 laser(CW 15kW)]

Oscillator
[Wave Guide Q-switched CO_2 laser]
Repetition rate:100kHz
Pulse width: 22ns

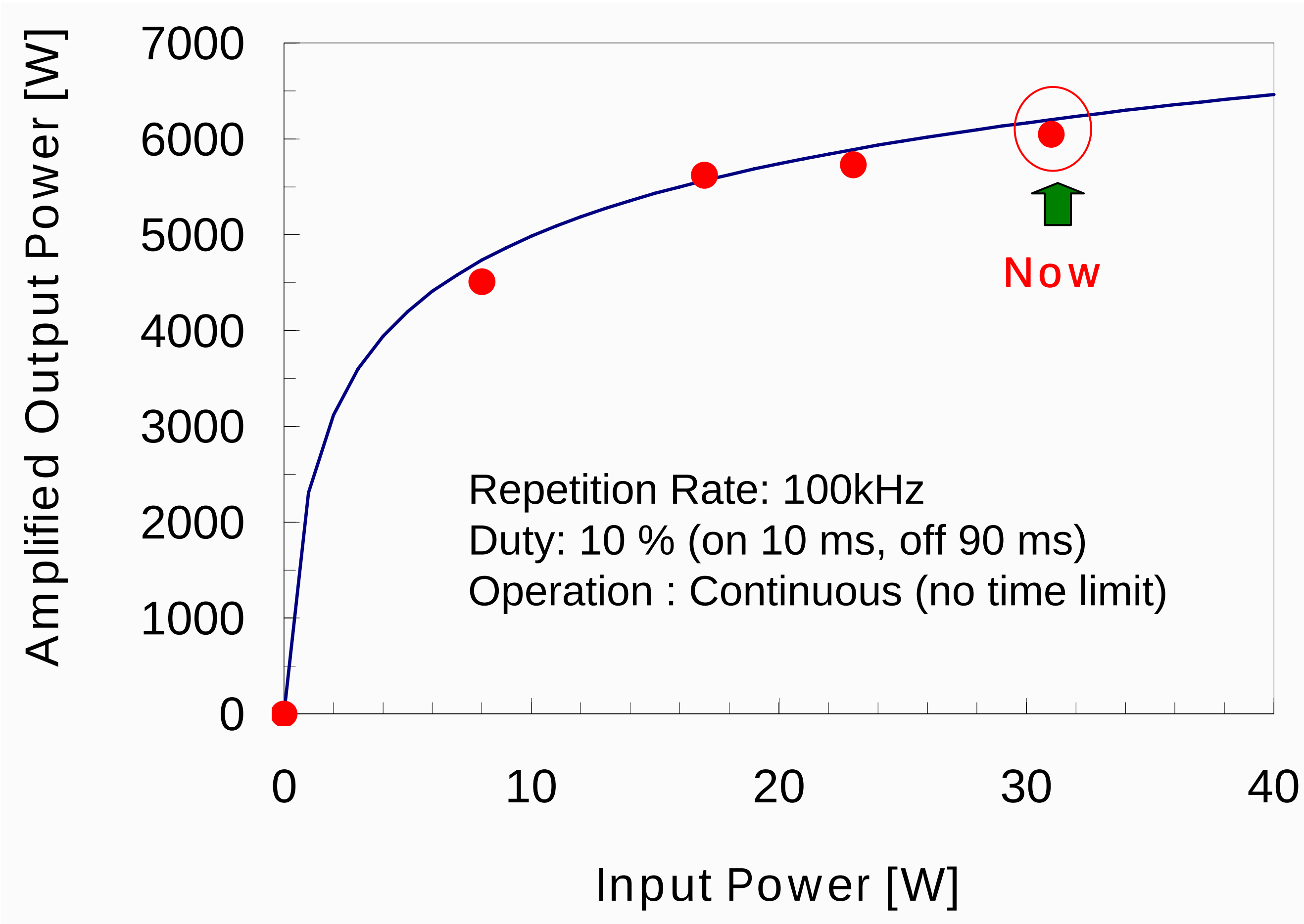


Pre-Amplifier
[Fast Axial Gas Flow RF-Excited CO_2 laser(CW 5kW)]



CO_2 Laser Average Output Power

High power experiment device



Amplification Characteristic of **3-Stage MOPA System**

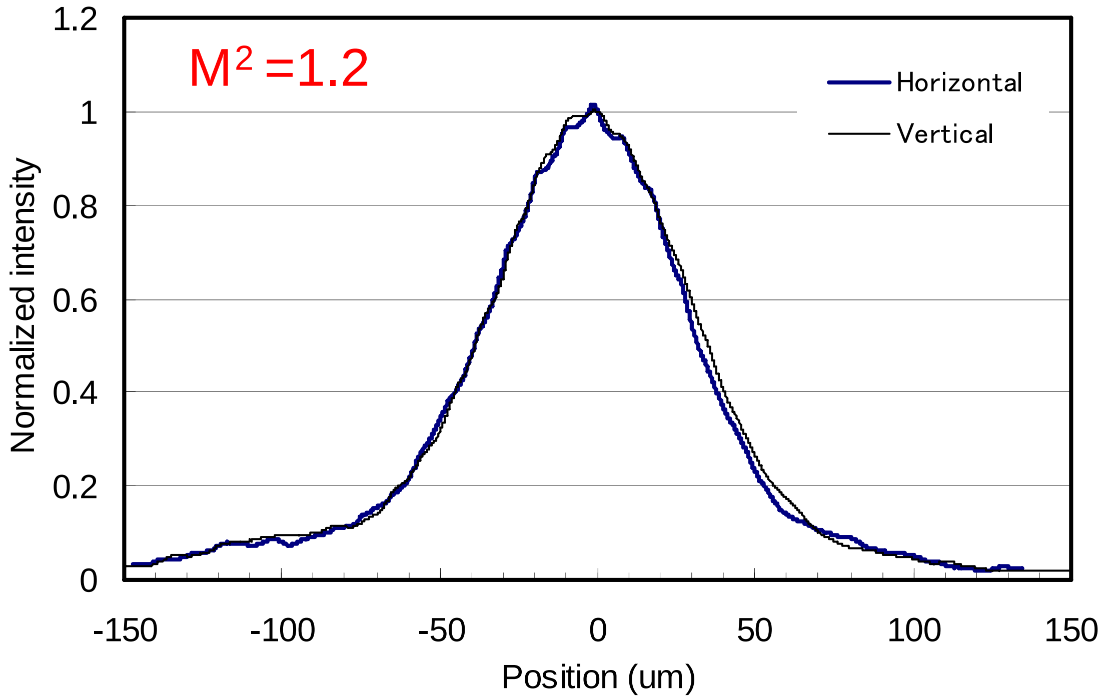
High laser beam quality

High power experiment device

M^2 : Before Amplification 1.0~1.2, After Amplification 1.2

⇒ Wavefront distortion caused by amplification is weak

CO_2 laser beam spot size (f=127 mm) about 100 um



- focus spot size observed after amplification ($1/e^2$) -

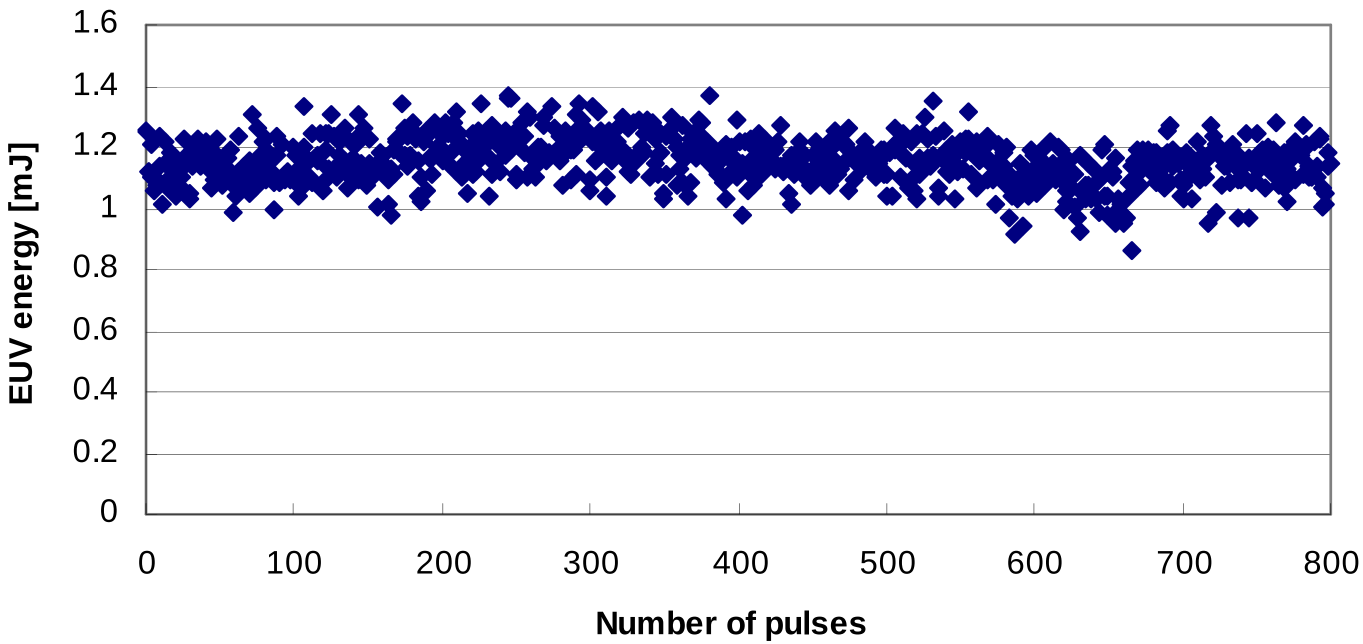
Horizontal: 135 μm Vertical: 137 μm

EUV from high power CO_2 laser produced Sn plasma

High power experiment device

EUV source power : **110 W** (2 πsr、2%bw)

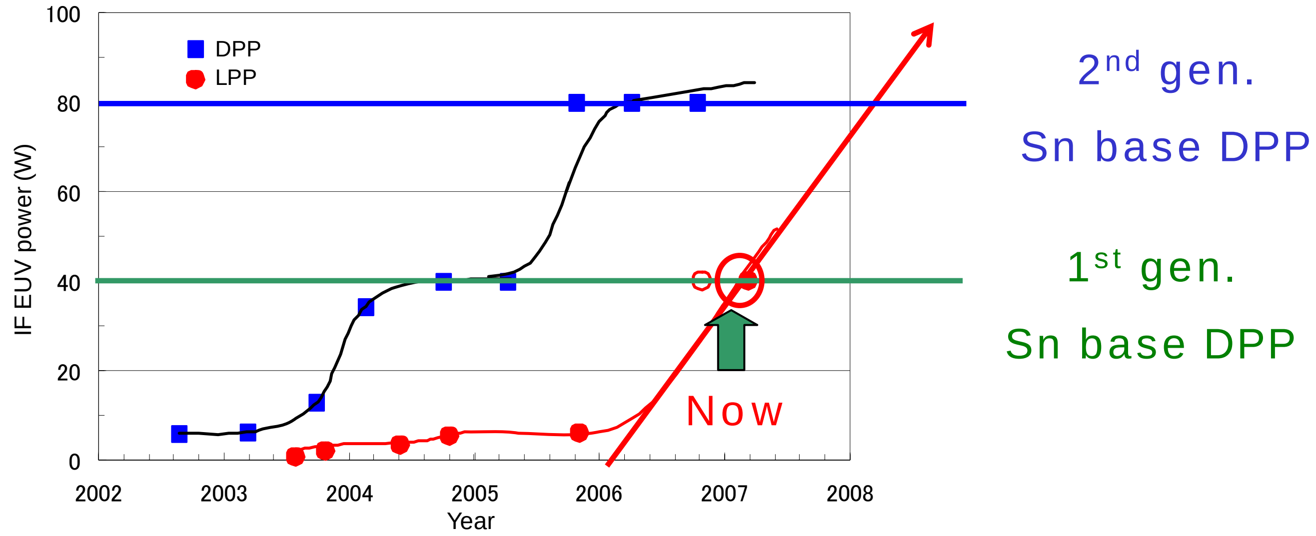
Target : Rotating Sn plate
Laser irradiation power : 5 kW
Conversion efficiency (Ce) : 2.2 %
EUV energy stability : 8% (3σ, 50 pulse)



LPP/ EUV Output Power

High power experiment device

LPP IF EUV power catch up the 1st gen. Sn base-DPP power level already !



Transmittance from primary to I/F	DPP		LPP	
Primary source EUV power (2pi sr, 2%bw)	616-702 W		110 W	
Debris shield transmission	0.8		1.0	
Collection angle & collector transmission	0.28		0.38	(4 sr, R=0.6)
Aperture (etendue limit & SPF) transmission	0.45	0.09	1.0	0.36
Gas transmission	0.9		0.94	
Usable EUV power after IF	55-62 W		40 W	w/o SPF

DPP data based on EUVA / DPP, October 2006

Sn debris and mitigation

Fundamental experiment device

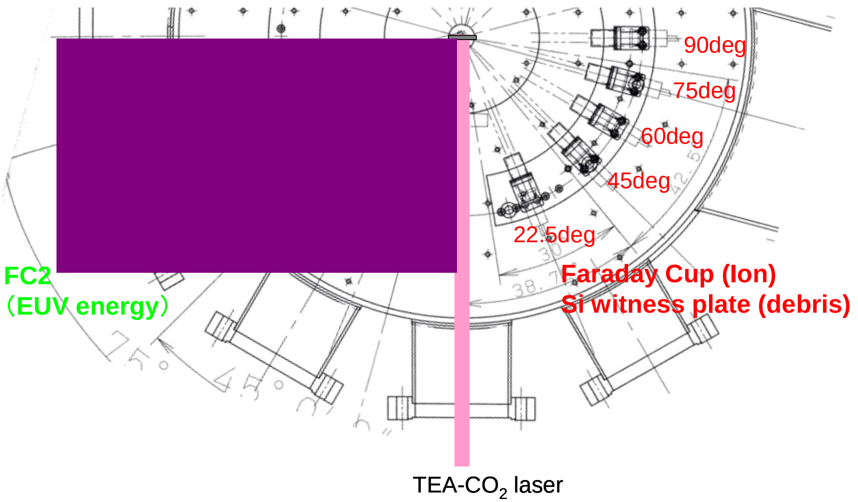
Debris from Sn laser plasma and mitigation

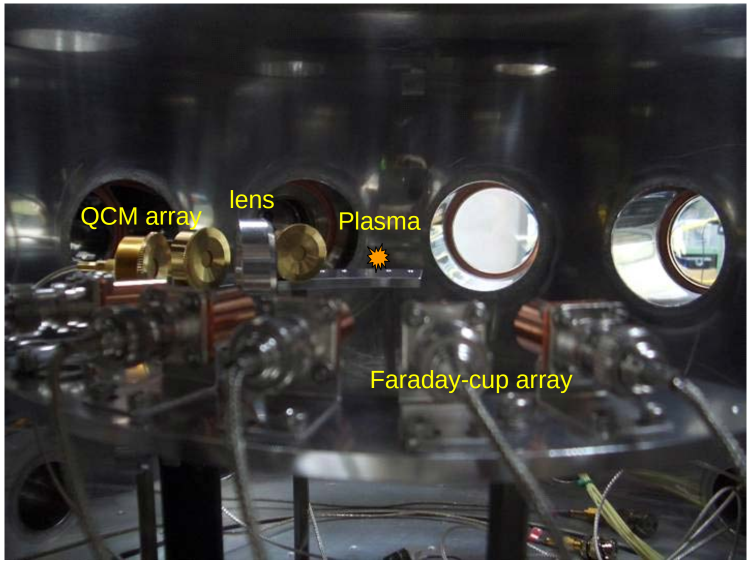
Droplet debris → **Deposition** ➡ **Minimized by CO_2 irradiation**

Sn neutral → **Deposition**, **Sputtering**

Fast ion → **Sputtering** ➡ Magnetic field mitigation

Experimental layout

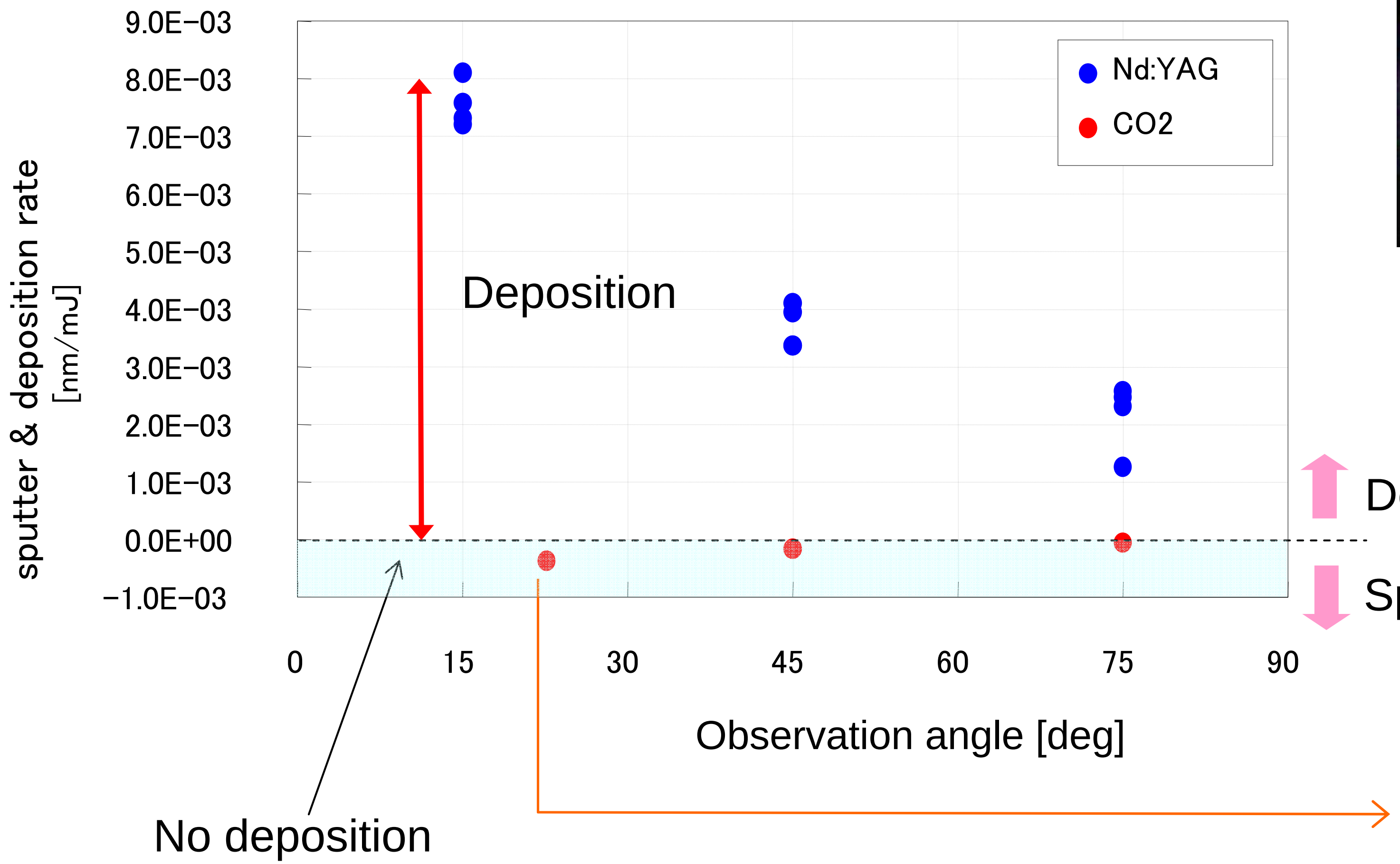


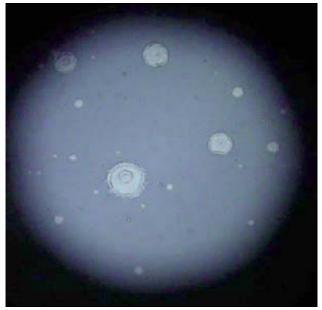


CO_2 laser is clean LPP driver compared to YAG

Fundamental experiment device

Sputter / deposition rate measured by QCM



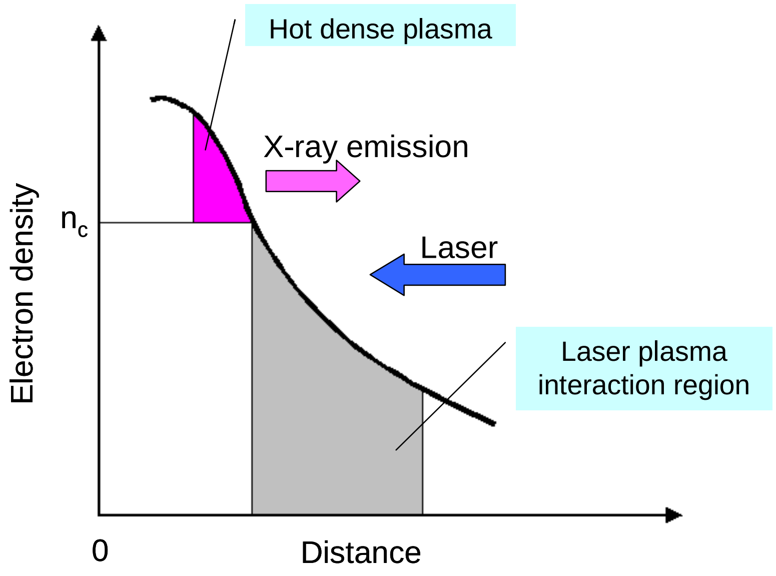


Deposition case

Refer to the poster presentation 6517-122 in detail.

CO_2 laser is clean LPP driver compared to YAG

Fundamental experiment device

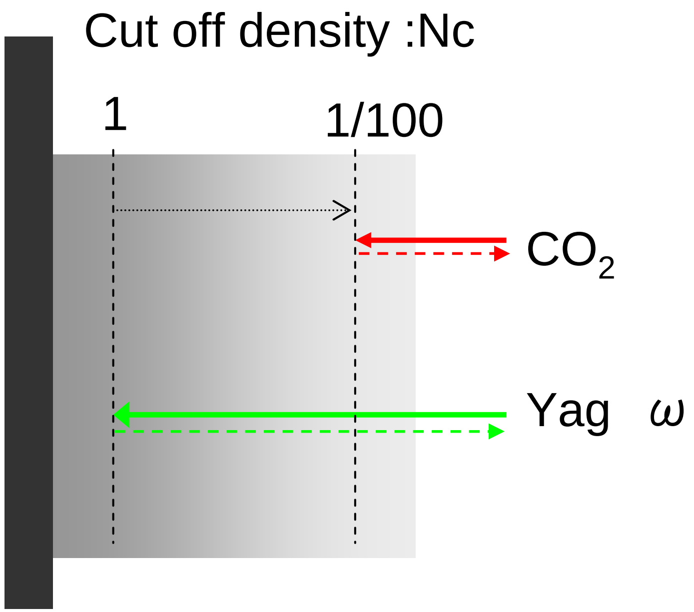


Efficient EUV is emitted from hot dense plasma near the electron critical density nc.

$$n_c = \frac{\varepsilon_0 m \omega^2}{e^2}$$

$$= \frac{1.11 \times 10^{21}}{\lambda^2} (cm^{-3})$$

λ: wavelength in μm



Laser	Electron critical density (cm^{-3})
CO_2 (10.6um)	1.0×10^{19}
Nd:YAG (1.06um)	1.0×10^{21}

CO_2 laser light is efficiently absorbed by low density plasma therefore thermal boiling of Sn (cause of Sn drops creation) is avoided.

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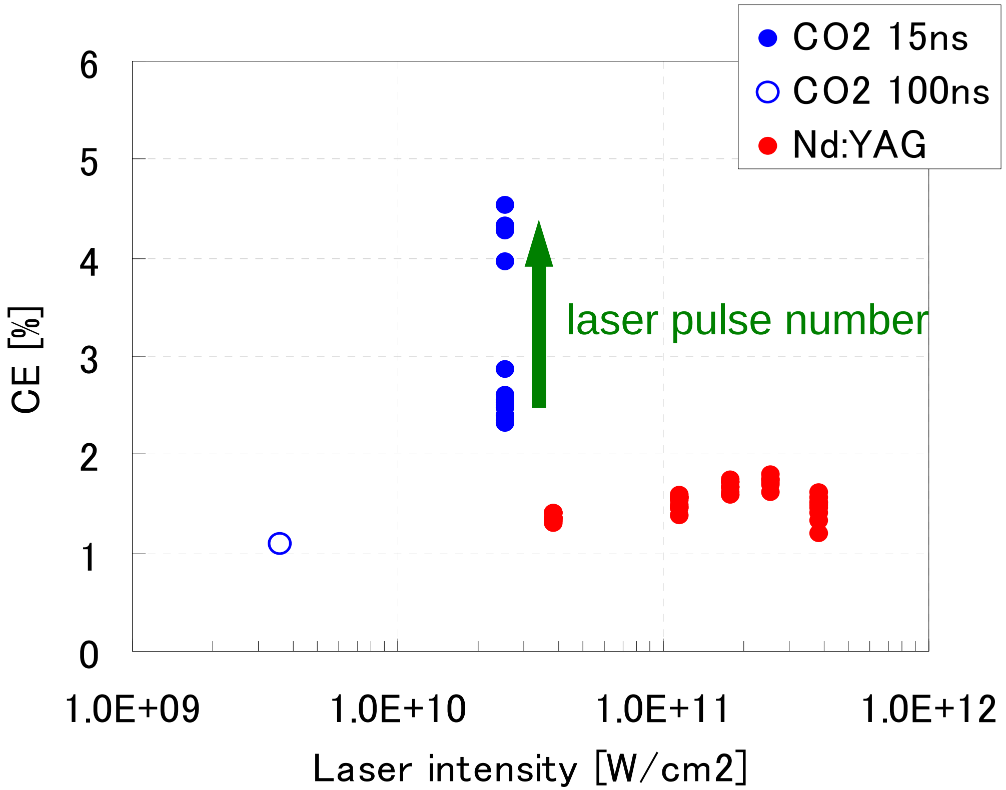
CO_2 laser + Sn LPP   Conversion efficiency

Fundamental experiment device

Conversion efficiency vs. laser wavelength, laser intensity and laser pulse number

1. Higher CE obtained at 10.6 um (CO_2) than at 1.06 um (Nd:YAG).
2. Higher CE obtained at lower laser intensity of 3×10^{10} W/cm^2 for CO_2.
3. CE increased with laser pulse number.

Target material : Sn plate
Spot size: d=100um

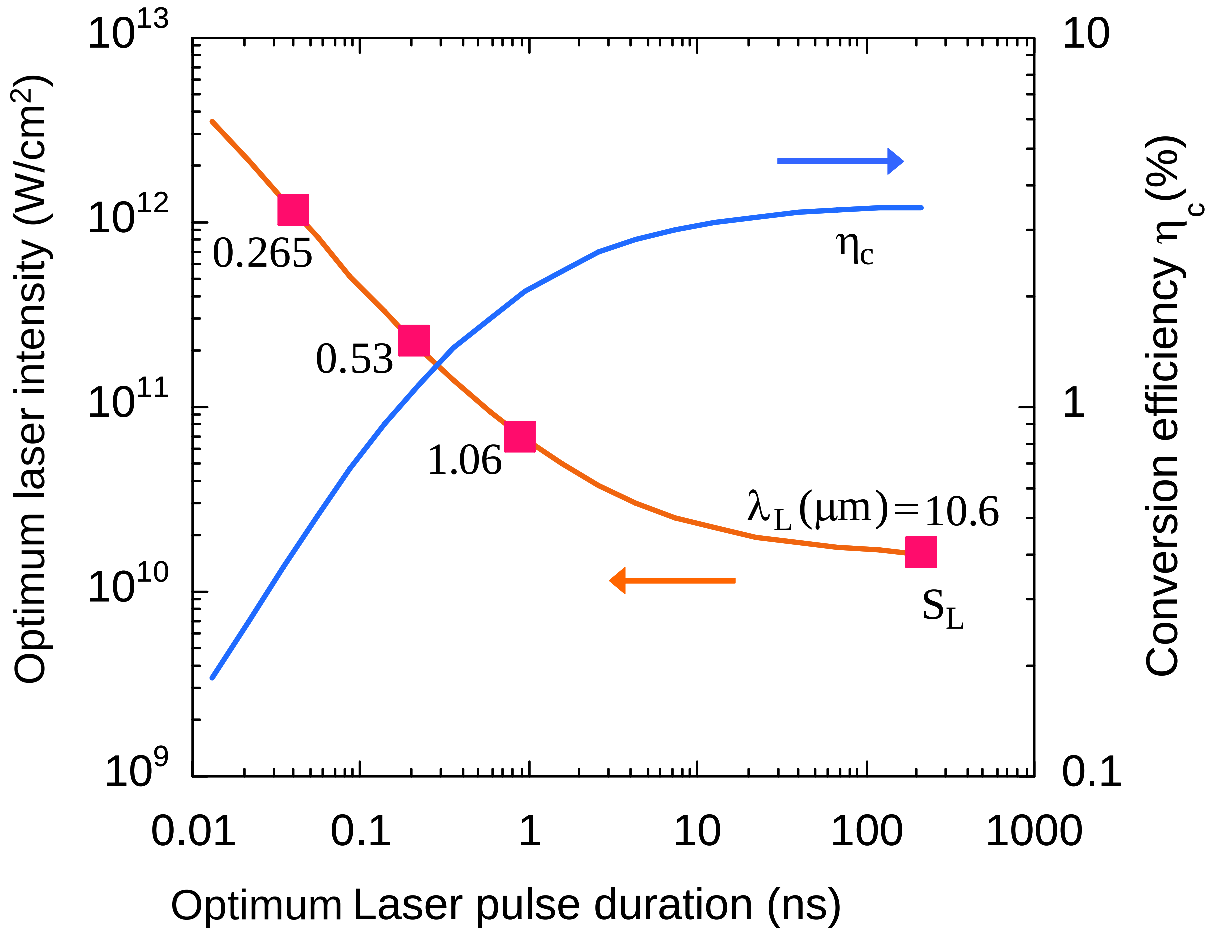


CO_2 laser + Sn LPP   Theoretical model

Fundamental experiment device

Self similar expansion model

Ref: M. Murakami et.al, Physics of Plasmas 13, 033107 (2006)



Characteristics of a CO_2 produced Sn plasma source

Fundamental experiment device

Target material: Sn

Items	CO2		Nd:YAG
CE	2.5 - 4.5%		1.5 - 2.5%
In band spectral bandwidth (nm, FWHM)	0.8		2.5
Debris		<	
Fast ion	1	:	2
Out-of-band		<	
Cost			
Initial	1	:	2 - 3
CoO (exclude electricity)	1	:	5
Mo/Si reflectivity at laser wavelength	> 90%		30%

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LPP/EUV future direction to HVM (1)

EUV power estimation with laser power & Ce

CE % / Laser kW	2.0	2.2	2.5	3.0	3.5	4.0	4.5
2.5	14	15	18	21	25	28	32
	18	20	23	27	32	36	41
5.0	28	31	35	42	49	56	63
	36	40	45	54	63	72	81
7.5	42	46	53	63	74	84	95
	54	59	68	81	95	108	122
10.0	56	62	70	84	98	112	126
	72	79	90	108	126	144	162

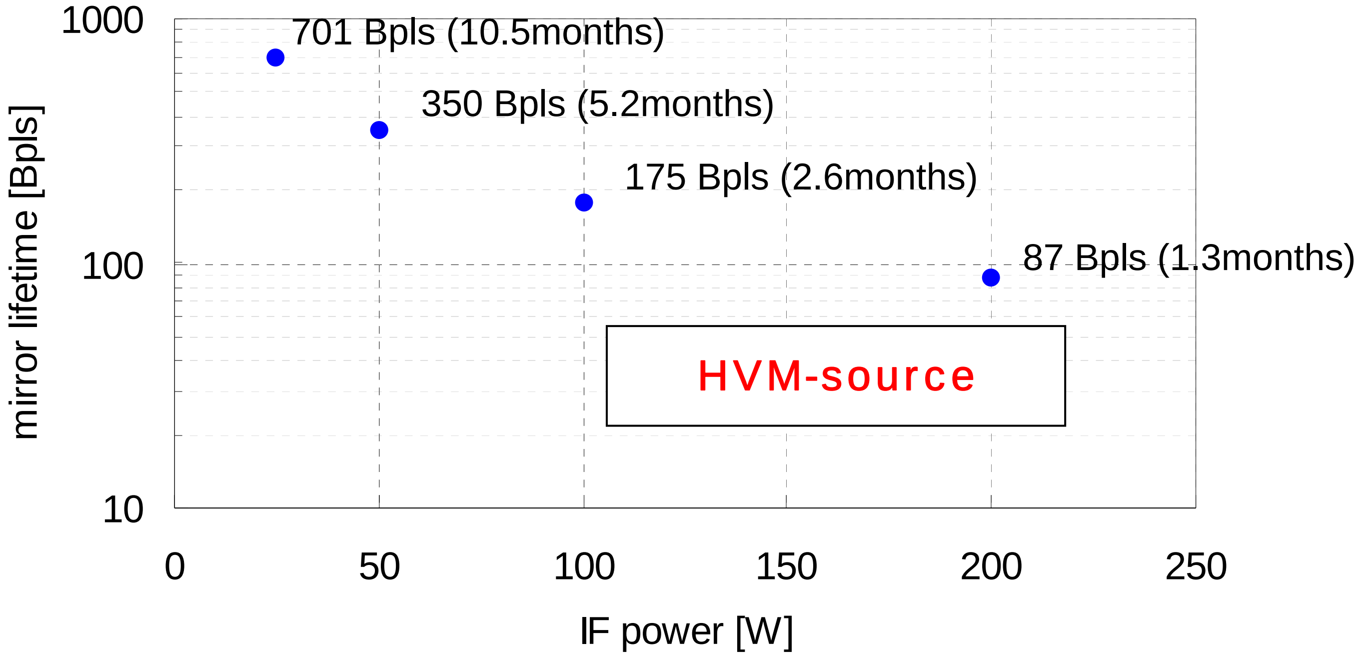
HVM-source

Transfer efficiency from primary source to IF

	Total	Debris shield	Collectable angle	Reflectivity	T%	SPF
Case1	0.28	0.8	5sr	0.6	0.9	0.8
Case2	0.36	1	4sr	0.6	0.94	1

LPP/EUV future direction to HVM (2)

Collector mirror lifetime estimation base on this work



Lifetime requirements (12months) : 80Bpls@10kHz ⇒ 800Bpls@100kHz

Mirror lifetime estimation based on
Rep.rate : 100kHz, CO_2 laser w/o pre-pulse
Mirror : Mo/Si 250 bilayer , 22.5deg(worst place)
Plasma-mirror distance : 150mm
Magnetic field effect : ×1000

Tool duty: 25%

7days 24H operation

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Summary

- 40W EUV @I/F equivalent power demonstrated with CO_2 drive laser and Sn target. This result means LPP source caught up with the IF power level of DPP source. The source power is 110 W (2pi sr, 2%bw).

  This result has been achieved with:

  - 6 kW RF CO_2 laser at 100kHz, 20ns (irradiation power 5kW)

  - Rotated Sn disk target

- Debris of CO_2 laser produced Sn plasma shows marvelous promising data.

  - Very small deposition of Sn on collector mirror

  - Droplet debris free Sn plasma

- Fundamental experiment and mature theory shows conversion efficiency can be higher than 4.5% at 3 x 10^{10} W/cm^2
- We estimate future power scalability with laser power & Ce, and mirror lifetime.
- As conclusion; The CO_2 laser + Sn target LPP light source is the most promising candidate of HVM EUV source. Not only scalability and higher efficiency but also long collector mirror lifetime for HMV-source.
- As a next step, we plan a 50W (@ I/F) demonstration system combining CO_2 drive laser and Sn debris mitigation in a single device.